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**(2)** ANALYSIS OF CLOUD RADIATIVE FORCING AND FEEDBACK IN A CLIMATE GCM

**(3)** *Scientific Goals:* The principal objectives of the research supported by ARM at the Goddard Institute for Space Studies (GISS) are: (1) to improve and validate the radiation parameterizations in the GISS GCM through model intercomparisons with line-by-line calculations and through comparisons with ARM observations, (2) to use ARM data to develop improved radiative treatment of clouds and aerosols in the GCM and to study the interaction of dynamics and radiation, and (3) to improve the GISS GCM diagnostic output to enable more effective comparisons to global cloud/radiation data sets. The GCM radiation model is specifically designed to enable the study of global climate and climate feedbacks in response to changes in radiative forcing over decadal time scales due to changes in atmospheric greenhouse gases and aerosols, including their direct and indirect effect on clouds. For this purpose, the GCM radiation utilizes the Single Gauss Point (SGP) doubling/adding algorithm to reproduce precisely the solar zenith angle dependence of reflected radiation compared to rigorous doubling/adding results for conservative scattering for all values of cloud optical depth and particle size. For LW calculations, the model uses the correlated k-distribution for the principal absorbing gases ($H_2O$, $CO_2$, $O_3$, $CH_4$, $N_2O$, and CFCs) to accurately reproduce atmospheric heating and cooling rates compared to line-by-line calculations. The GCM radiation model is also designed to produce narrow-band and angle dependent radiances for more direct comparisons of GCM radiation results with satellite measurements such as AVHRR, ERBE and SCARAB. A further objective is to compare and validate GCM cloud and aerosol input parameters with retrieval results from MFRSR and RSS measurements. To begin addressing the question of aerosol composition, size, shape, and radiative properties, and their role in aerosol/cloud interactions, we have acquired RSP polarimetric measurements during the March 2000 Cloud IOP.

**(4)** *Recent Accomplishments:*

(1) An emission angle dependent parameterization to correct longwave fluxes for multiple scattering at thermal wavelengths has been implemented. The effect reduces the emission to space from top level clouds and increases their greenhouse efficiency globally by about 1.5 $Wm^{-2}$, and also increases the downward thermal flux incident on the ground by several tenths of a watt compared to the more typical treatment of no scattering at thermal wavelengths.

(2) Based on laboratory measurements, a parameterized treatment has been developed to model the dependence of aerosol radiative properties as functions of relative humidity due to changing aerosol size and refractive index. Applied to the GCM's hygroscopic sulfate, nitrate and sea salt aerosols, the relative humidity dependence increases the aerosol scattering efficiency and optical depth by a factor of several for relative humidities in excess of 90%.

(3) Treatment for sub-grid height dependent cloud heterogeneity has been implemented in the GISS GCM radiation code derived from rigorous Monte Carlo radiative transfer simulations [Cairns *et al*. 2000]. In the parameterization, the radiative effects of sub-grid cloud heterogeneity are accurately represented by existing plane-parallel radiative transfer applicable for homogeneous clouds.

(4) Cloud radiative properties (solar, thermal, and spectral) are parameterized to be fully responsive to small changes in cloud particle size, liquid/ice phase, as well as to cloud optical depth and sub-gridbox cloud heterogeneity. Non-spherical T-matrix results for the spectral dependence of ice cloud extinction and scattering for solar and thermal wavelengths is used to model cirrus radiative properties.

(5) To demonstrate the capabilities of polarimetry an instrument called the Research Scanning Polarimeter (RSP) has been developed by SpecTIR Corporation and was operated by NASA GISS and Columbia University during the March 2000 Cloud IOP. The measurements in each instantaneous field of view in a scan provide the simultaneous determination of the intensity, and the degree and azimuth of linear polarization in all nine spectral bands.

(6) During the Cloud IOP on the 8th 9th and 10th of March 2000, the RSP instrument was used to make polarimetric measurements from a Cessna 210 aircraft, acquiring high accuracy polarimetry over an 80° swath in both along-track and cross-track mode. This data is of particular interest for evaluating the spectral BRDF and surface inhomogeneity in a 10-km radius around the ARM central facility and is available to interested ARM team members.

(7) We continue to refine and validate retrieval algorithms to analyze MFRSR and RSS measurements that utilize the spectral dependence of the direct solar beam extinction as well as the measured diffuse-sky radiances. Since the approach relies on **relative** rather than absolute instrument calibration, the time series variations of column $NO_2$, $O_3$, and aerosol optical depth and particle size characteristics can be accurately determined from their spectral signatures.

**(5)** *Progress and Accomplishments Description:*

Since the GISS GCM is used to study global climate and climate feedbacks in response to changes in radiative forcing over decadal time scales due to changes in atmospheric greenhouse gases and aerosols, including their direct and indirect effect on clouds, the radiation model must be specifically designed to respond correctly to small changes in radiative forcing. For this purpose, the radiation model utilizes the Single Gauss Point (SGP) doubling/adding algorithm to reproduce the solar zenith angle dependence of reflected radiation compared to rigorous doubling/adding results for conservative scattering for all values of cloud optical depth and particle size. For LW calculations, the model uses the correlated k-distribution for the principal absorbing gases ($H_2O$, $CO_2$, $O_3$, $CH_4$, $N_2O$, and CFCs) to accurately reproduce atmospheric heating and cooling rates compared to line-by-line calculations. The emission angle dependent parameterization to correct longwave fluxes for multiple scattering at thermal wavelengths improves the precision of longwave fluxes with respect to multiple scattering contributions at thermal wavelengths. The effect multiple scattering reduces the emission to space from top level clouds and increases their greenhouse efficiency globally by about 1.5 $Wm^{-2}$ compared to the more typical treatment of no scattering at thermal wavelengths.

We have developed a parameterization, based on laboratory measurements [Tang and Munkelwitz 1981; 1994; 1996], to model aerosol radiative properties as functions of relative humidity due to changing aerosol size and refractive index. This parameterization is applied to the GCM's hygroscopic sulfate, nitrate and sea salt aerosols, which are a part of a comprehensive 50-year aerosol climatology that includes the time and spatial variation for 12 different aerosol types. With increasing relative humidity, the aerosol scattering efficiency and optical depth can increase by a factor of several, particularly for relative humidities above 90%. With a realistic relative humidity dependence of aerosol radiative properties, the GCM radiation field can be more effectively used to compared chemistry and transport model generated aerosol distributions (typically expressed as mass density distributions) with observational constraints on aerosol optical depth variations with season and geographic locations such as those obtained from AVHRR measurements [Mishchenko *et al.* 1999].

The GCM radiation model is also designed to facilitate intercomparisons of GCM calculated results with global observational data from AVHRR, ISCCP, ERBE, SCARAB, and other sources. From the solar radiation spectral and k-distribution intervals of the GCM radiation model, we have mapped a correspondence with Channel 1 and 2 of AVHRR measurements to make possible spectral albedo ratio

intercomparisons between GCM radiation results and AVHRR measurements. This enables GCM aerosol size and optical depth variations to be compared more directly to relevant satellite data [Mishchenko *et al.* 1999].

We continue to refine and validate retrieval algorithms to analyze MFRSR and RSS measurements that utilize the spectral dependence of the direct solar beam extinction as well as the measured diffuse-sky radiances. Since the approach relies on **relative** rather than absolute instrument calibration, the time series variations of column $NO_2$, $O_3$, and aerosol optical depth and particle size characteristics can be accurately determined from their spectral signatures. We have recently applied the same (MACE Analysis) technique to SAGE II measurements [Lacis *et al.* 2000] to derive vertical profiles of stratospheric aerosol optical depth and particle size, including also the height distribution of stratospheric $NO_2$, $O_3$, and water vapor.

To demonstrate the capabilities of polarimetry, an instrument called the Research Scanning Polarimeter (RSP) has been developed by SpecTIR Corporation and was operated by NASA GISS and Columbia University during the March 2000 Cloud IOP. This instrument uses a polarization compensated scan mirror assembly to scan the fields of view of six boresighted, refractive. The refractive telescopes are paired, with each pair making measurements in three spectral bands. One telescope in each pair makes simultaneous measurements of the linear polarization components of the intensity in orthogonal planes at 0° and 90° to the meridional plane of the instrument, while the other telescope simultaneously measures equivalent intensities in orthogonal planes at 45° and 135°. This approach ensures that the polarization signal is not contaminated by scene intensity variations during the course of the polarization measurements, which could create false polarization. The measurements in each instantaneous field of view in a scan provide the simultaneous determination of the intensity, and the degree and azimuth of linear polarization in all nine spectral bands.

During the Cloud IOP on the 8th, 9th, and 10th of March 2000, the RSP instrument was used to make polarimetric measurements from a Cessna 210 aircraft. High accuracy polarimetry was acquired over an 80° swath in both along-track and cross-track mode. The along-track data provides similar analysis opportunities to POLDER and MISR data (but with far greater spectral range and a larger number of spectral of channels), while the cross-track data is similar to the solar reflectance measurements provided by MODIS (but with the inclusion of polarization). The spectral bands are located in the visible/near infrared at 410 (30), 470 (20), 550 (20), 670 (20), 865 (20), and 960 (20) nm and in the shortwave infrared at 1590 (60), 1880 (90), and 250 (120) nm, where the parenthetic numbers are the FWHM of each band. This data is being processed and will be made available to interested ARM team members. It is of particular interest for evaluating the spectral BRDF of the surface and the surface inhomogeneity in a 10km radius around the

ARM central facility. It is also being analyzed to test the accuracy with which aerosol properties can be retrieved from a downward looking polarimetric instrument and to determine the validity of an empirical surface polarization model, developed by Nadal and Breon, for the surface encountered in the Southern Great Plains.

**(7)** *Recent Refereed Publications Supported by DOE ARM:*

Alexandrov, M.D., and A.A. Lacis, 2000:  A new three-parameter cloud/aerosol particle size distribution based on the generalized inverse Gaussian density function.  *Applied Math. and Comp.*, (in press).

Cairns, B., A.A. Lacis, and B.E. Carlson, 2000:  Absorption within inhomogeneous clouds and its parameterization in General Circulation Models.  *J. Atmos. Sci.*, (in press).

Chowdhary, J., B. Cairns, M.I. Mishchenko, and L.D. Travis, 2000:  Retrieval of aerosol properties over the ocean using multispectral and multiangle photopolarimetric measurements from the Research Scanning Polarimeter.  *Geophys. Res. Lett.*, (submitted).

Lacis, A.A., B.E. Carlson, and J.E. Hansen, 2000:  Retrieval of atmospheric $NO_2$, $O_3$, aerosol optical depth, effective radius and variance information from SAGE II multi-spectral extinction measurements.  *Applied Math. and Comp.*, (in press).

Ma, Q., and R.H. Tipping, 2000:  The density matrix of $H_2O$-$N_2$ in the coordinate representation:  A Monte Carlo calculation of the far-wing line shape.  *J. Chem. Phys.,* **112**, 574-584.

Mishchenko, M.I., I.V. Geogdzhayev, B. Cairns, and A.A. Lacis, 1999:  Aerosol retrievals over the ocean using channel 1 and 2 AVHRR data: a sensitivity analysis and preliminary results.  *App. Opt.*, **38**, 7325-7341.

Mishchenko, M.I., and A.A. Lacis, 2000:  Manifestations of morphology-dependent resonances in Mie scattering matrices.  *Applied Math. and Comp.*, (in press).

Moreau, G., J. Boissoles, C. Boulet, R.H. Tipping, and Q. Ma, 2000:  Theoretical study of the collision-induced fundamental absorption spectra of $O_2$-$O_2$ pairs for temperatures between 193 and 273 K.  *J. Quant. Spectrosc. Radiat. Transfer,* **64,** 87-107.

**(8)** *ARM Science Team Meeting Extended Abstracts:*

Alexandrov, M., B. Cairns, A. Lacis, and B. Carlson, 1999: Analysis of MFRSR data: sensitivity of retrievals to instrumental problems. *Proceedings of the Ninth Atmospheric Radiation Measurement (ARM) Program Science Team Meeting* (March 22-26, 1999, San Antonio, TX).

Cairns, B., M. Alexandrov, A.A. Lacis, and B.E. Carlson, 1999: Polarimetry of aerosols. *Proceedings of the Ninth Atmospheric Radiation Measurement (ARM) Program Science Team Meeting* (March 22-26, 1999, San Antonio, TX).

Lacis, A.A., B. Cairns, C. Delo, and W.B. Rossow, 1999: GCM aerosols and sub-grid cloud heterogeneity. *Proceedings of the Ninth Atmospheric Radiation Measurement (ARM) Program Science Team Meeting* (March 22-26, 1999, San Antonio, TX).

Alexandrov, M., B. Cairns, A. Lacis, and B. Carlson, 2000: Remote sensing of atmospheric aerosols, trace gases, and water vapor by means of MFRSR: validation and sensitivity studies. *Proceedings of the Ninth Atmospheric Radiation Measurement (ARM) Program Science Team Meeting* (March 13-17, 2000, San Antonio, TX).

Cairns, B., M. Alexandrov, A.A. Lacis, and B.E. Carlson, 2000: Constraints on diffuse solar irradiance. *Proceedings of the Ninth Atmospheric Radiation Measurement (ARM) Program Science Team Meeting* (March 13-17, 2000, San Antonio, TX).

Lacis, A.A., V. Oinas, and B. Cairns, 2000: Parameterized correction of longwave scattering by clouds in the GISS GCM. *Proceedings of the Ninth Atmospheric Radiation Measurement (ARM) Program Science Team Meeting* (March 13-17, 2000, San Antonio, TX).


**(9)** Publications listed as (submitted) on previous FY progress report have either been published or are listed above as (in press).